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*Interpretation of Results from Surveyor  
Alpha-Scattering Experiment*

Alden A. Loomis

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PASADENA, CALIFORNIA

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April 30, 1964

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## ABSTRACT

Many ambiguities are inherent in chemical analyses if they are used alone to interpret a rock genetically. Furthermore, rocks at the surface of the Moon may differ from rocks below the surface because of contamination by meteoritic infall, sputtering, and extensive mixing by impact. Nevertheless, the broad categories of igneous rocks and meteorites which are familiar on Earth are the best compositional models for rocks on the Moon. Anhydrous igneous rocks and meteorites may be categorized on the basis of the atomic percentage of oxygen:

- a. below 50% — sputtered rocks and those with free metal in excess of chondrites
- b. 50 to 56% — chondritic meteorites
- c. 57 to 58½% — dunites and olivine-rich peridotites
- d. 58½ to 60% — peridotites and pyroxenites
- e. 60 to 61% — basalts, some alkalic derivatives
- f. 61 to 64% — siliceous derivatives, some alkalic rocks

The Si/Na ratio is another reliable chemical parameter on which to base further subdivisions of genetic importance; terrestrial anhydrous igneous rocks and meteorites occupy well-defined fields in a plot of oxygen percentage vs Si/Na. The best parameter to resolve ambiguities in such a plot is the Mg/Si ratio. The chief drawback to such a quantitative interpretation is the accuracy with which the alpha-scattering analyses are made. More sophisticated subdivisions could be made if Ca and K could be separated. Classification schemes which use iron as an indicator of rock type or of differentiation of lunar rocks should not be used.

The concurrence of high Mg/Si and Mg/Na ratios with oxygen contents over 59–60% will indicate water in the sample. The amount of water can be estimated by balancing the cations and anions in the actual analysis.

Concomitant measurements of the magnetic susceptibility and bulk density of the sample would aid considerably in the chemical interpretation. Television of the analyzed spot and the area surrounding the spacecraft is necessary to supply megascopic rock texture, structure, and field relations data.

K J T H O R

## I. INTRODUCTION

This Report investigates the interpretation of the data to be provided by the alpha-scattering experiment on the *Surveyor I* spacecraft. A major step in the petrologic exploration of the Moon is to determine the mechanical and chemical conditions under which the sample formed in order to identify lunar processes and evaluate their relative effects in the evolution of the Moon. In most cases, the chemical analysis of a rock has far less interpretive value than either its texture or its mineralogy. The history of a rock is determined from the minerals it contains and the geometrical relationships among the mineral grains, not merely the abundances of the elements that are present. The possibility of being misled in a genetic interpretation of a simple analysis is great. Nevertheless, certain conclusions can be drawn with some probability of success if given certain chemical parameters.

Contamination by meteoritic infall, sputtering, and mixing of surface rock types cannot be evaluated separately on the basis of chemical analyses alone. The interpreter must keep such inherent ambiguities in mind while he interprets the alpha-scattering analysis in terms of more simplified petrological models. In this Report, the compositions of igneous rocks and meteorites will be used as the simplified models because those chemical groups have the greatest chance of being the main components in the composition of an unknown lunar rock. Volcanic names will be applied to rock compositions wherever possible instead of their plutonic equivalents. All analyses and concentrations will be given in atomic percent calculated hydrogen-free.

## II. DATA FROM ALPHA-SCATTERING EXPERIMENT

The figures given below for resolution, sensitivity, accuracy, and matrix effects were taken from publications by experimenters E. Franzgrote and A. Turkevich (Refs. 1 and 2), or from personal conversations with E. Franzgrote.

### A. Assumptions About Type and Quality of Data

The experiment will be assumed to provide an elemental analysis of the sample stated as atomic percentages of the total number of atoms with atomic number ( $Z$ ) greater than 4(Be). The instrument will resolve elements in groups of  $Z$ . It will discriminate signals for adjacent elements only through  $Z = 17(\text{Cl})$ . Resolution is  $2Z$  from  $Z = 18(\text{Ar})$  to  $26(\text{Fe})$ , and degrades progressively to  $Z = 92(\text{U})$ , where discrimination is only in groups of 10  $Z$ . The threshold sensitivity level will be about 1% for all resolution groups except for C, Th, and U, where sensitivity is 0.1, 0.01, and 0.01% respectively. In the absence of certain matrix effects, the accuracy of the analysis for any resolved element or group of elements will be assumed to be  $\pm 1\%$  of the total sample;

i.e., a true value of 50% should be analyzed between 49 and 51%, and a true value of 2%, between 1 and 3%.

### B. Matrix Effects

#### 1. Effect of Hydrogen

Hydrogen is 20 to 25% of the sample in some common hydrous mafic and ultramafic rocks. It will act only as a low-density transparent matrix material; the analysis for elements with  $Z > 4$  will automatically be normalized to 100%, excluding  $Z = 1$  to 3.

#### 2. Effect of Density Variations Excluding Free Iron

Matrix effects due to differences in mineral density or to variations in atomic number from a standard sample will cause errors of  $\pm 2\%$  of the amount present.

#### 3. Effect of Free Iron

Free iron intermixed with silicate or other less-dense minerals will cause errors up to about  $\pm 10\%$  of the

amount present. An independent measurement of the magnetic susceptibility of the sample would be of great help in interpreting the alpha-scattering results.

### C. Geometrical Effects

The relative abundances of the elements will not be affected by the source-to-sample distance. Surface irregularities of the sample will be small because a scattering angle of nearly  $180^\circ$  will be covered in the experiment.

### D. Practical Results of the Resolution, Sensitivity, and Accuracy Obtainable

The resolution obtainable will preclude clear separation of K from Ca. These two elements vary antithetically in most rock series; the total for both will be of relatively little value.

Fe and Ni cannot be separated; one analytical figure will give the total for Fe + Ni(+ Mn + Co).

The minimum sensitivity will equal or exceed the total amounts present of *some* of the common rock-forming elements in almost any given case. Therefore, the error for Al, Fe, Mg, Na, and other less-common elements may be 100% or more of the amount present

for any given sample. The relative accuracy of the analysis for O and Si will be high because of the large amounts of each expected to be present.

The accuracy of the analysis for Na (as well as several other elements of lesser petrological importance) will be enhanced by analyses of protons emitted in alpha-proton nuclear reactions.

### E. Effect of Sputtered Sample

The process of sputtering, in which lunar surface materials are chemically reduced by the action of solar emanations, will possibly have greatly changed the character of the sample from its original state. The main chemical effect presumably will be a reduction of the number of oxygen atoms which will leave free metals. A partially-sputtered sample will be difficult to distinguish chemically from one which originally had some free metal in its mineral assemblage. Rocks with free iron are familiar as meteorites on Earth, but such igneous rocks may be forming on the surface of the Moon. The possible existence of  $C_2$  radicals and  $H_2$  in gas emanations from the Moon shows that some igneous rocks could be reduced enough to contain free metals. The problem of assessing metal/oxygen ratios will be discussed in Section IV B.

## III. SOME SAMPLE LUNAR PETROLOGIC MODELS

A lunar petrologic model for each type of lunar terrain (e.g., highlands, maria, ejecta blankets, crater walls, etc.) is not only of scientific but of practical importance. The purpose of the petrologic model is to describe the processes active in the development of the Moon; an understanding of such processes is the key to predicting the nature of the lunar surface at any given point.

### A. Particular Models

All of the sample models below may or may not be affected by contamination by meteoritic infall, by mixing with other lithologies because of impact, by sputtering

of surface rocks, and by interstitial deposition near the surface of materials dissolved in volcanic gases or other internally-generated fluid phases. The products of all of these processes will be indistinguishable on a chemical basis alone except in some cases where they completely dominate the sample. They all will provide great, perhaps insuperable difficulties to correct interpretation of the chemical data in most possible cases. Some of the many possible models are listed below, not necessarily in order of probability of occurrence:

- a. Original cold Moon, no internal melting, no rock differentiation. Ultramafic rocks most probable,

perhaps hydrated locally. Surface dominated by impact features. Crystalline rocks may not exist in top several kilometers.

- b. Old lunar crust, the product of early differentiation. Little crystal-liquid fractionation would lead to rocks with composition of basalts or Ca-rich achondrites. More extreme crystal-liquid separation would lead to rhyolite or trachyte ("granitic") composition, depending upon rate of silica concentration. Little activity late in history of Moon so that surface is dominated by impact. Hard crystalline rocks close to surface at many points.
- c. Advanced differentiation along alkaline trend. Silica concentrated slowly relative to alkalis. Rock compositions include basalt, hawaiite, mugearite, trachyte, phonolite. The common sequence on Earth in nonorogenic regions; a likely case for the Moon. Lavas very viscous, so ash-fall and ash-flow sheets will be extensive. Very irregular surfaces in areas of exposed rocks. Small fault scarps, domes, etc. will be common.
- d. Advanced differentiation along calc-alkaline trend. Silica concentrated rapidly. Rock compositions include basalt, andesite, dacite, rhyolite. Occurs on Earth in orogenic belts. Irregular surface features with much ash.
- e. Hydrous phases deposited from ascending vapors being driven out of interior by radiogenic heating. Minerals would include nitrates, sulfates, carbonates, hydroxides, borates, halides, oxides. Could occur with any of the models above, filling interstices in granular or vesicular materials.

## B. Concentrations of Important Elements

The most important elements in any unsputtered lunar sample from the interpretive point of view and the *probable* limits of their concentration ranges (calculated hydrogen-free) are listed in Table 1.

**Table 1. Most important elements and their expected concentration ranges calculated hydrogen-free in atomic percent**

Element	Z	Probable limits of concentration, atomic %	Igneous rock types used for estimated range
B	5	0- 1	(max) Volcanic sublimate
C	6	0-15	(max) Carbonaceous chondrite
O	8	50-65	(min) Enstatite chondrite (max) Siliceous igneous rock
F	9	0- 1	(max) Igneous rock or sublimate
Na	11	0.5-7	(min) Chondrite (max) Phonolite
Mg	12	0.2-25	(min) Rhyolite (max) Dunite
Al	13	1- 9	(min) Ultramafic (max) Phonolite
Si	14	15-30	(min) Dunite (max) Quartz-rich rock
S	16	0- 5	(max) Carbonaceous chondrite or volcanic sublimate
Cl	17	0- 1	(max) Igneous rock or sublimate
Ca(+ K)	20(19)		
Ti	22	0.1- 1	(max) Alkalic differentiates, ferrogabbros
Fe(+ Ni)	26(28)	0.5-15	(min) Magnesian or siliceous igneous rock (max) High-iron chondrite

## IV. IMPORTANCE OF SELECTED CHEMICAL PARAMETERS

### A. General Statement

Several methods of combining elemental abundances from a rock analysis are used on Earth for describing the differentiation trends of terrestrial rocks. Some of these cannot be applied to analyses from the alpha-scattering experiment because potassium cannot be separated from calcium. The major elements available then are O, Si, Al, Fe, Mg, and Na.

The question here is, which elements can best be used in attempts to characterize lunar rocks and to estimate the extent and manner of differentiation? The answer appears to be as follows:

- a. O and Si are best from the point of view of accuracy because they commonly are the most abundant elements; an error of  $\pm 1\%$  of the total sample means an error of less than 6% of the amount present for Si and 2% for O.
- b. Fe should not be used because the likelihood of meteoritic contamination is great, sputtering may selectively concentrate iron, and a ratio of iron to some other element may not be an adequate indicator of differentiation on the Moon. Pursuing the last point particularly, the fugacity of oxygen in crystallizing magmas on Earth determines the rate at which iron is concentrated in the liquid during crystal-liquid separation. Fayalite ferrogabbros in the Skaergaard intrusion have 8 to 9% Fe and are highly differentiated rocks. If the oxygen fugacity had been higher, the result would have been a much more siliceous or alkalic rock because the presence of  $\text{Fe}^{3+}$  would have caused early precipitation of magnetite and early depletion in iron. If the oxygen fugacity had been lower, free iron might have crystallized early leaving an iron-poor residual liquid. Oxygen fugacities in lunar magmas need not have the same range of values as in Earth magmas, and iron should not be used as an indicator of differentiation.
- c. Of the three elements remaining — Al, Mg, and Na — the analytical accuracy should be proportional to their relative abundances. All are commonly low-abundance elements except Mg in ultramafic rocks and stony meteorites. None of these three elements should be used with another in a ratio, because the error for each may amount to 25 to 100% of the

amount present. Of the possible combinations with the more plentiful elements Si and O, the Si/Na ratio seems to best characterize petrologically important groups of rocks when plotted against the absolute oxygen percentage. The ratio Mg/Si can be used to resolve the few ambiguities which occur with the Si/Na vs O scheme, such as separating highly differentiated ferrobasalts (or Ca-rich achondrites) from normal basalts and identifying hydrous rocks.

### B. Metal/Anion Ratio

The most plentiful element in almost any rock is oxygen. The other anions, F, Cl, and S occur in small amounts. In terrestrial igneous anhydrous rocks, the oxygen percentage could be a fairly sensitive indicator of differentiation. However, three factors which are impossible to evaluate independently combine to strip any lunar metal/oxygen ratio of genetic significance *in itself*:

- a. Contamination by meteoritic free iron
- b. Sputtering which may have produced oxygen-deficient samples
- c. Hydration of ferromagnesian minerals to produce chlorite, brucite, serpentine, etc. (see Section VI)

The effects of meteorite contamination, native free iron in lunar rocks, and sputtering, probably cannot be separated and evaluated. A low-anion sample, one in which total oxygen plus halogens and sulfur is not greater than the quantity demanded to produce a normally-oxidized assemblage, is one where  $\text{O} + \text{F} + \text{Cl} + \text{S}$  is less than about 57%. Chondritic meteorites with free Fe-Ni show a progressive change from 56 to 50% oxygen (plus 1.5 to 2.5% sulfur) depending upon the amount of free Fe-Ni present; 56% oxygen for 3% Fe-Ni and 50% oxygen for 30% Fe-Ni. Rocks with below 50% total anions do not exist on Earth or among stony meteorites; any lunar sample with total O, F, Cl, and S below 50% must represent excess meteoritic iron or a sputtered sample, or both.

Anhydrous rocks on Earth have oxygen contents between 57 and 65%. The extremes are a dunite  $(\text{Mg}, \text{Fe})_2\text{SiO}_4$ ,  $(\text{Fe}, \text{Cr})_3\text{O}_4$  in which the minerals both are  $4/7 = 57\%$  oxygen, and a granite  $\text{SiO}_2$ ,  $\text{KAlSi}_3\text{O}_8$ ,  $\text{NaAlSi}_3\text{O}_8$  in which the minerals are 66.7 and 61.5% oxygen. Dunites, peridotites, and pyroxenites all fall in

the 57 to 60% oxygen range. Basalts (and the Ca-rich achondritic meteorites) have about 60 to 61% oxygen. Further differentiates in the rock series that contain free quartz have oxygen contents increasing toward 65%. Differentiates that concentrate alkalis faster and have no free quartz have oxygen contents between 60 and 62%. Silicic and subsilicic differentiates must be distinguished on the basis of other chemical properties to be discussed below.

The effect of hydration, e.g., serpentinization of a dunite, will be to raise the oxygen percentage as seen in the alpha-scattering data because hydrogen is not

counted. The formula for serpentine is  $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$ , which would be  $9/14 = 64\%$  oxygen. Serpentinized ultramafic rocks thus have oxygen contents equivalent to more siliceous or alkalic rocks, but can be separated from them on the basis of their Mg/Si ratios (Section VI).

Rocks fall naturally, then, into the following groups based on oxygen percentage:

- below 50% — sputtered rocks and those with free metal in excess of chondrites
- 50 to 56% — chondritic meteorites
- 57 to 58½% — dunites and olivine-rich peridotites

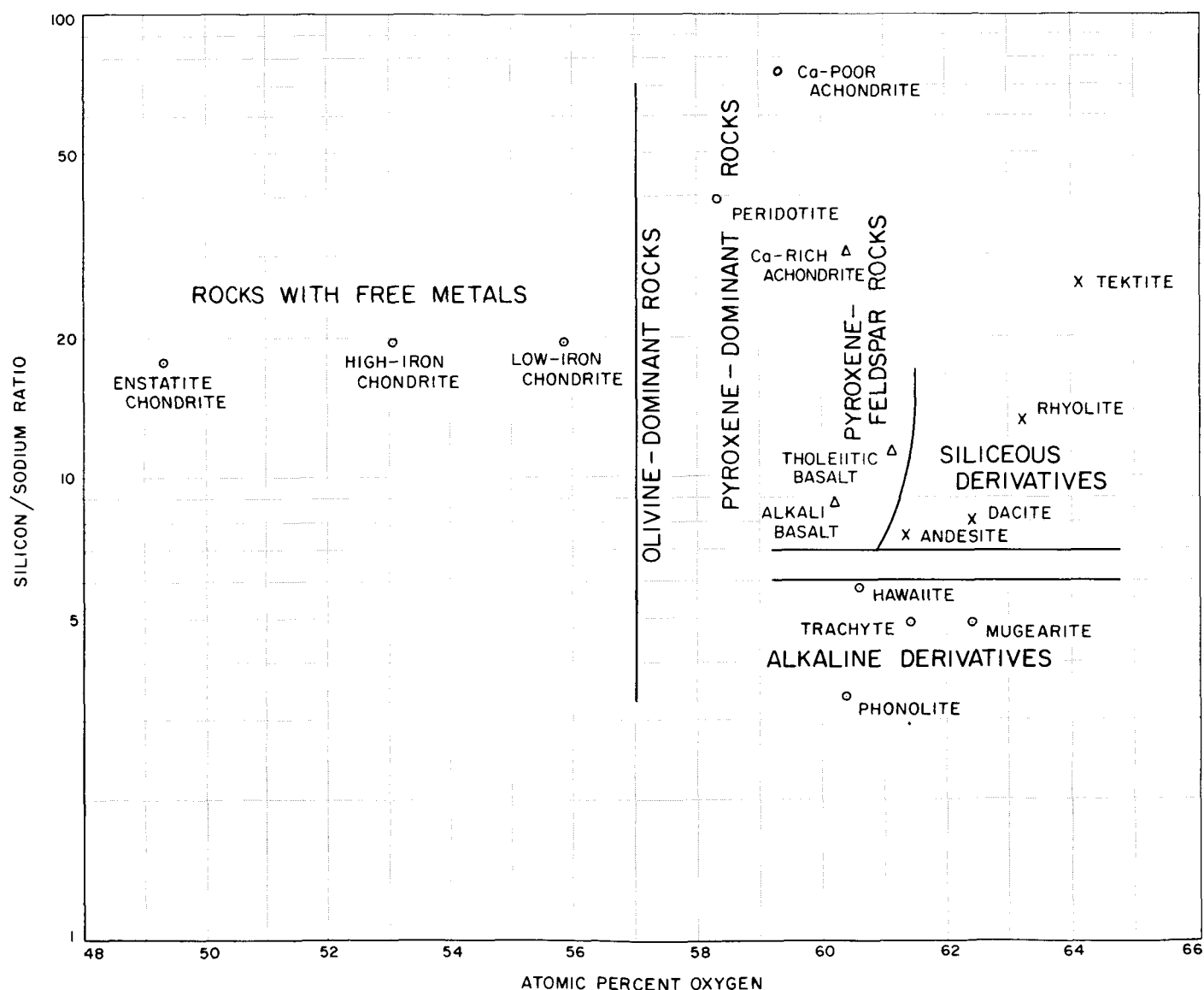


Fig. 1. Fields of common rocks in plot of Si/Na ratio vs oxygen percentage

- d. 58½ to 60% — peridotites and pyroxenites
- e. 60 to 61% — basalts, some alkalic derivatives
- f. 61 to 64% — siliceous derivatives, some alkalic derivatives.

The siliceous and alkalic derivative rocks can be separated by their Si/Na ratios.

### C. Silicon/Sodium Ratio

The ratio of silicon to sodium separates rocks into natural groups: ultramafic and meteoritic rocks have

Si/Na > 15; basalts and siliceous derivative rocks have Si/Na between 7 and 15; alkaline rocks have Si/Na < 6. A combination of the Si/Na oxygen-percentage groupings separates most rocks into well-defined fields. Figure 1 is a representation of such a plot, with values for several important rock types shown within the various fields. The analyses used in Figure 1 are listed in Table 2. The major problem of using the Si/Na ratio is the accuracy with which the sodium analysis can be made. Sodium is commonly only about 3% of the sample; an analytical accuracy of 1% would lead to a reading of between 2 and 4%. The Si/Na ratio would be uncertain by a factor of 2. The proton spectra for sodium should

Table 2. Analyses used in construction of Fig. 1 in atomic percent, calculated hydrogen-free

Analysis	Si	Al	Fe(Ni,Mn)	Mg	Ca+K	Na	O	S	Si/Na
Basaltic									
a. tholeiitic	18.9	6.2	3.7	3.5	4.5	1.6	61.1		11.8
b. alkali basalt	17.0	6.4	3.7	5.2	4.7	1.9	60.2		8.9
Alkaline									
c. hawaiiite	18.0	6.9	3.5	2.6	3.3	3.2	60.6		5.8
d. mugearite	19.9	5.3	3.0	1.3	3.3	4.1	62.4		4.9
e. alkali trachyte	22.0	7.5	0.8	0.3	3.2	4.5	61.4		4.9
f. phonolite	20.2	8.5	1.2	0.3	3.2	6.0	60.4		3.4
Calc-alkaline									
g. andesite	19.7	7.3	2.7	2.4	3.6	2.6	61.4		7.6
h. dacite	22.4	6.9	1.5	1.1	2.7	2.7	62.4		8.0
i. rhyolite	25.6	5.5	0.6	0.2	2.7	2.0	63.2		12.7
Ultramafic									
j. peridotite	15.8	1.7	3.7	18.4	1.5	0.4	58.3		40
Meteoritic									
k. tektite	26.6	5.2	1.0	0.3	1.4	1.2	64.1		26
l. Ca-rich achondrite	18.3	5.2	5.3	5.5	4.3	0.6	60.3		30
m. Ca-poor achondrite	18.7	0.5	4.8	16.2	0.5	0.25	59.2		75
n. low-iron chondrite	16.1	1.3	9.7	14.9	1.0	0.8	55.9	1.6	19.6
o. high-iron chondrite*	15.6	1.2	13.4	14.8	1.0	0.8	53.0	1.7	19.5
p. enstatite chondrite*	16.3	1.9	18.4	12.4	0.7	0.9	49.3	4.8	18.0

\* Carbonaceous chondrites are similar to o and p, but should show carbon and nitrogen.

References to Table 2 analyses: a, b, d, e, f, g, h, i, j—Nockolds (Ref. 3); c—Macdonald (Ref. 4); k—Barnes (Ref. 5); l, m, n, o, p—Urey and Craig (Ref. 6).

help considerably in obtaining better analytical accuracy. The sodium analysis from proton spectra is largely a matter of counting statistics, and the result would be worth the extra analysis time necessary to reduce the error to below  $\frac{1}{2}\%$  of the total sample.

#### D. Magnesium/Silicon Ratio

The Mg/Si ratio can best be used to resolve ambiguities which may arise in the interpretation based on the

parameters of Fig. 1, Si/Na vs O. Strongly hydrated samples will have much higher oxygen percentages than their anhydrous equivalents; an Mg/Si ratio of more than 0.5 will indicate that the sample is probably an undifferentiated ultramafic rock or of chondritic composition. Also, most basalts have Mg/Si between 0.15 and 0.4; highly differentiated ferrogabbros or ferrobasalts have Mg/Si less than 0.1 and can be separated on that basis from normal basalts which might have become contaminated with meteoritic iron.

## V. NATURE AND CLASSIFICATION OF ROCKS

### A. Genetic Classifications

The common classifications of rocks are based on parameters other than chemical composition. The fundamental problem of interpreting alpha-scattering data will be to erect as good a genetic classification scheme as possible using only chemical criteria. This section describes the standard methods of interpreting rocks and their relative importance; it is this system of interpretation which the chemical data are being called upon to supplant.

The important factors in a genetic interpretation of rocks are:

- a. Texture
- b. Mineral assemblage and composition of the minerals
- c. Time of the crystallization or accumulation of the rock relative to other rocks in association with it or other rocks of a like nature
- d. Bulk chemistry of the rock

Classifications of rocks are made on the basis of the first two of the above—texture and mineral assemblage. The general chemical equivalence of rhyolites and granites requires that a textural and mineralogical observation be made in order to determine whether or not the rock is volcanic or plutonic. This simple separation is impossible with chemical data alone, but is of great importance to estimates of the nature of the surrounding

surface as well as lunar processes. The separation of igneous rocks from recrystallized or accumulated clastic rocks also commonly requires a textural identification. Thus, the major divisions of the accepted rock classification schemes are based primarily on texture and are important genetically. Table 3 shows the most common genetic classification and is based on both textural differences and field relationships:

Most subdivisions of rock types within these groups are made on the basis of mineral assemblages and relative proportions of certain minerals. Using igneous plutonic (coarse-grained) rocks as an example, they are found statistically to fall in several groups: those with more than 10% quartz, those with less, and groups containing the feldspathoid minerals. Rock names within these groups are assigned on the basis of relative proportions of the most common minerals in the rocks—feldspars and feldspathoids, pyroxenes, olivine. Bulk mineralogical data are therefore needed to determine rock types within the broad textural classifications. Mineral chemical

Table 3. Genetic classification of rocks

Igneous	Sedimentary	Metamorphic
a. Volcanic b. Plutonic	a. Accumulated clastic b. Chemically precipitated from aqueous solution at planetary surface	a. Recrystallized without major chemical change b. Replacement with chemical change

composition and the relative abundances of the major phases can be used to compute an approximate chemical analysis of the bulk sample. The reverse process—calculation of the mineral compositions and abundances from a chemical analysis—always must be done under assumptions about the conditions of formation, usually that the mineral assemblage formed in chemical equilibrium and not, for example, as a mechanical mixture of accumulated particles. Knowledge of both rock texture and bulk mineralogy are therefore essential for a genetic interpretation of an unknown rock.

### B. Ambiguities Inherent in Chemical Analyses Alone

A chemical analysis of a sample would apparently have great scientific value in the event that the results are clearly interpretable as a "perfect" granite, basalt, chondrite, etc. Such value would be small, however, because the nature of the rock texture or its mineralogy would still be unknown. A good illustration of the ambiguity inherent in chemical analyses unsupported by other data is in the group of rocks with the chemical composition of basalt. Chemical analyses of the following rock types could not be separated except for a somewhat higher water content in e and f.

- a. basalt flow
- b. basalt ash and pumice bed
- c. intrusive gabbro pluton
- d. amphibolite
- e. epidote-albite-chlorite schist
- f. glaucophane schist
- g. eclogite

Some of the rocks differ in texture, some in mineralogy, some in both. A sample analysis from the literature for each of the rocks above is listed for reference in Table 4. The alpha-scattering experiment will not provide an analysis which is as complete as those in Table 4, mainly because it will be unable to determine hydrogen or distinguish between Ca and K. The analyses are listed hydrogen-free, but the actual hydrogen present is included in parentheses for reference.

**Table 4. Analyses from the literature\* for eight different rocks of basaltic composition (Analyses in atomic percent, hydrogen-free. Actual hydrogen percentage in parentheses. Note how oxygen percentage varies with the amount of hydration)**

Rock	a	b	c	d	e	f	g	h
Si	18.1	18.5	17.5	18.5	18.4	17.6	18.0	18.2
Al	6.4	6.1	8.1	7.1	7.2	6.2	6.1	5.1
Ti	0.4	0.8	0.4	0.5	1.2	0.3	0.3	0.1
Fe	3.6	3.4	2.9	3.4	2.9	2.7	3.9	5.4
Mg	3.9	3.8	4.2	3.2	2.2	4.5	3.7	5.5
Ca+K	4.7	4.9	4.2	3.9	2.2	3.9	4.8	4.2
Na	2.0	1.6	1.7	2.4	3.2	1.7	2.7	0.6
O	61.9	60.9	60.8	61.6	62.7	63.1	60.5	60.8
H	(2.4)	(0.3)	(1.0)	(3.0)	(6.9)	(10.5)	(1.4)	(1.0)

\*a. Waters (Ref. 7), No. 3, basalt flow.

b. Muir and Tilley (Ref. 8), p. 120, No. 2, basalt ash and pumice bed.

c. Wager and Deer (Ref. 9), average chilled border gabbro.

d. Clark (Ref. 10), p. 603, No. B, amphibolite.

e. Wiseman (Ref. 11), p. 360, epidote-albite-chlorite schist.

f. Borg (Ref. 12), p. 1568, No. a, glaucophane schist.

g. Borg (Ref. 12), p. 1574, No. a, eclogite.

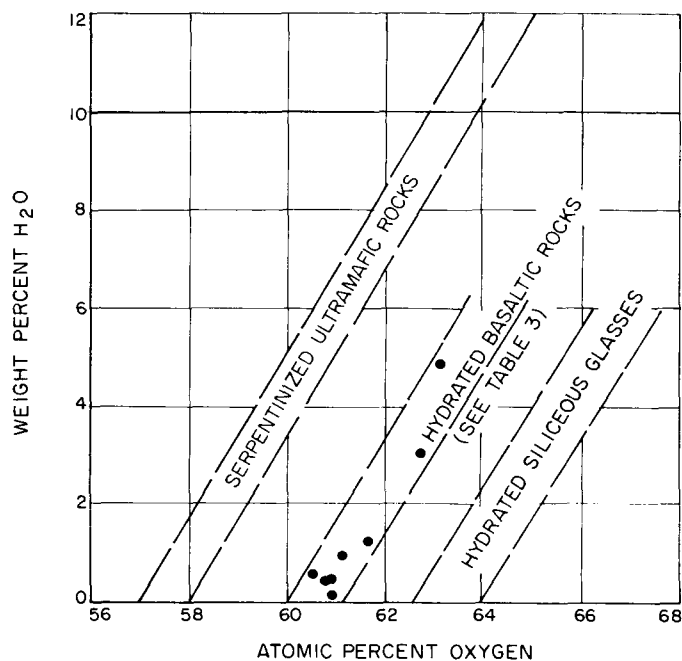
h. Urey and Craig, (Ref. 6), p. 68-69, average Ca-rich achondrite.

The analysis of Urey and Craig's average Ca-rich achondritic meteorite differs chiefly in FeO and  $\text{Al}_2\text{O}_3$ , and is listed as column h. Any of the analyses, if received from the Moon, would be immediately interpreted by most people as from a basalt. Such a designation could be extremely misleading. The genetic implications of the textural differences between the igneous and metamorphic rocks in Table 4 are important with respect to the thermal and tectonic history of the Moon. The  $P$ ,  $T$ ,  $P_{\text{H}_2\text{O}}$  stability fields, for example, of the alternative ferromagnesian minerals chlorite, pyroxene, and glaucophane, are different and very important to an estimate of the conditions under which rocks in the upper several kilometers of the Moon have evolved.

## VI. TEST FOR WATER IN THE SAMPLE

The concurrence of an Mg/Si ratio of over 0.5 (see Section IV D) with an oxygen content of over 59 to 60% will indicate water in an ultramafic sample. Oxygen will be higher than in the anhydrous equivalent rock because the hydrogen in the water will not be detected in the analysis and the remaining elements will be normalized to 100%. A completely serpentinized dunite has an oxygen percentage of about 64% and a water percentage by weight of about 12%. The increase in oxygen percentages for the analyses of rocks of basaltic composition in Table 4 is from about 60½ to 63% for rocks which contain up to 5% water by weight. Hydrous rhyolitic glasses with 5% water by weight have their oxygen contents increased from about 63 to 66%. Figure 2 is a graph illustrating the change of oxygen percentage caused by changes in water content for serpentinized ultramafic rocks, hydrated basaltic rocks, and siliceous volcanic rocks.

The amount of water in a lunar sample can probably be estimated best by balancing the cations and anions in the actual analysis if the rock is low in iron, sulfur, and carbon. Enough singly-charged hydrogen ions must be present to balance any excess anionic charge. However, iron may occur as the free element, or as  $\text{Fe}^{2+}$  or  $\text{Fe}^{3+}$ . All three oxidation states could exist together near the surface of the Moon because rocks with both ferrous and ferric iron may have become contaminated by meteorites or selectively sputtered. The total cation charge of the sample cannot be estimated accurately if iron is plentiful. Sulfur is the most common element in rocks which acts either as a cation as in sulfates, an anion as in sulfides, or as a free element; occurrences of carbon or nitrogen as anions are unlikely. Decisions as to whether sulfur is positively or negatively charged, or neutral, may



## VII. MEANING OF DATA FROM OTHER EXPERIMENTS

The television experiment will aid greatly in an interpretation of the chemical data. The TV must provide as much evidence as to the megascopic texture and field relationships of the rocks as possible. It must be known whether the analysis is being conducted on an isolated block, a rough vesicular surface, a loose layer of dust, or a surface covered with whiskers or small euhedral crystals. It must be known if individual crystals in the rocks are visible on a scale of millimeters. It must be known if the lithologic unit being analyzed is extensive or restricted, whether protuberances above the surface show blocky fractured shapes or rounded volcanic shapes. The only real hope of correctly interpreting the chemical data in many instances will be because photographs have sup-

plied the lacking textural and field data necessary for classifying rocks.

Experiments aimed at measuring the physical properties (bearing strength, etc.) of the surface will not aid the chemical interpretation because of the unknown effects of impact and sputtering processes.

As mentioned previously, a measurement of the magnetic susceptibility would be of great help in interpreting the elemental analysis and in estimating the amount of water in the sample. A measurement of bulk density would be of value, but is not as important.

## VIII. ESTIMATION OF LUNAR SURFACE PROPERTIES

Chemical data alone cannot provide information that is superior to TV in any way. A chemical estimation requires various theoretical petrological models for the surface properties to be expected from any given process. The delineation and development of such models is outside the scope of this Report. However, two hypothetical examples will be suggested to illustrate the possibilities:

- 1) If the Moon originated by accretion of particulate materials and the temperature of the body of the Moon has not reached the melting point, the structure of the surface will have been produced primarily by impact processes. Crystalline rocks would not exist in the top few kilometers of the Moon if

the temperature has not been high enough to cause recrystallization of the original particles. The distribution of the various surface features could be attacked by statistical analysis.

- 2) If volcanic activity has produced extensive lava flows, the surface will be quite irregular and rough on scales from a millimeter to several meters. The surfaces of basalt flows on the Moon, for example, should be rougher than those on equivalent flows on Earth for several reasons. The chemical analysis of a sample which is likely a volcanic rock will suggest that large surface areas may be quite variable in physical characteristics, and hazardous to objects moving on the surface.

## REFERENCES

1. Franzgrote, E., "Compositional Analysis by Alpha Scattering", *Jet Propulsion Laboratory Space Programs Summary No. 37-20*, Vol. IV, pp. 186-190, April 30, 1963.
2. Turkevich, A., *Proposal for Chemical Analysis of Lunar Surface Material Using Alpha Particle Bombardment*, II, NASA Headquarters No. SC-7572, 1962.
3. Nockolds, S. R., "Average Chemical Composition of Some Igneous Rocks", *Bulletin of the Geological Society of America*, Vol. 65, pp. 1007-1032, 1954.
4. Macdonald, G. A., "Dissimilarity of Continental and Oceanic Rock Types", *Journal of Petrology*, Vol. I, pp. 172-177, 1960.
5. Barnes, V. E., "North American Tektites", *University of Texas Publication*, Vol. 3945, pp. 477-582, 1940.
6. Urey, H. C., and Craig, H., "The Composition of the Stone Meteorites and the Origin of the Meteorites", *Geochimica et Cosmochimica Acta*, Vol. 4, pp. 36-82, 1953.
7. Waters, A. C., "Stratigraphic and Lithologic Variations in the Columbia River Basalt", *American Journal of Science*, Vol. 259, pp. 583-611, 1961.
8. Muir, I., and Tilley, C. E., "The Tholeiitic Basalts of Mauna Loa and Kilauea", *American Journal of Science*, Vol. 261, pp. 111-128, 1963.
9. Wager, L. R., and Deer, W. A., "Petrology of the Skaergaard Intrusion, Kangerdlugssuaq, East Greenland", *Meddelelser om Gronland*, Bd. 105, Nr. 4, 352, 1939.
10. Clark, F. W., "The Data of Geochemistry", *U. S. Department of the Interior, Geological Survey, Bulletin 770*, p. 841, 1924.
11. Wiseman, J. D. H., "The Central and Southwest Highlands Epidiorites", *Quarterly Journal of the Geological Society of London*, Vol. 90, pp. 354-417, 1934.
12. Borg, I. Y., "Glaucophane Schists and Eclogites near Healdsburg, California", *Bulletin of the Geological Society of America*, Vol. 67, pp. 1563-1584, 1956.